

RESPONSE MATRIX OF A BSS/<sup>6</sup>Li(Eu)

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## ABSTRACT

Using Monte Carlo methods the response matrix of a Bonner sphere spectrometer with a  $^6\text{LiI}$  scintillator has been calculated. The response was calculated for 0, 5.08, 7.62, 12.7, 20.32, 25.4, and 30.48 cm-diameter polyethylene spheres using twenty three monoenergetic neutron sources whose energy varies from  $2.50\text{E}(-8)$  to 100 MeV. The response functions were interpolated to thirty one and fifty one neutron energies and compared with two response functions reported in the literature, a good agreement was found from this comparison. Main differences were found for neutrons whose energy is larger than 20 MeV. For UTA4 response functions differences are also noticed in the lower energy neutrons. These differences are mainly attributed to the cross sections libraries utilized in the different studies.

## INTRODUCTION

In 1960 the multisphere spectrometer, also known as Bonner sphere spectrometer, BSS, was introduced in the aim to measure the neutron spectrum (1). This spectrometer is a set of polyethylene spheres with different diameters with a thermal neutron detector that is located at the centre of the spheres. With the BSS the neutron spectrum from thermal to 20 MeV can be obtained, the spectrometer's response is extended up to few GeV neutrons by adding intermediate shells of lead in the moderating spheres. (2, 3)

Several thermal neutron detectors are utilized in BSS, such as  $^6\text{LiI}(\text{Eu})$  scintillator (4), pairs of thermoluminescent dosimeters (5, 6), activation foils (7, 8), track detectors (9), and,  $\text{BF}_3$  or  $^3\text{He}$  filled proportional counters (10, 11). Due to polyethylene moderating feature each sphere-detector combination has a particular response function. The spectrometer response matrix is the set of response functions.

Inside a neutron field the detector, bare o inside of any sphere, produces a count rate,  $C$ , that is related to the response matrix,  $R_\Phi(E)$ , and the neutron spectrum,  $\Phi_E(E)$ , through the Fredholm integral equation of the first kind, shown in equation 1.

$$C = \int R_\Phi(E) \Phi_E(E) dE \quad (1)$$

Technological limitations prevent the experimental determination of the response functions using monoenergetic neutrons, therefore response functions have been calculated using the one-dimensional discrete ordinates transport code ANISN (12), Monte Carlo methods with the MCNP code (13, 14), MCNPX code (11), and high-energy codes (3).

The aim of this work is to calculate the response matrix of a Bonner spectrometer with a  ${}^6\text{LiI}$  scintillator using Monte Carlo methods with updated cross section libraries and to compare with the M&S and UTA4 response matrices.

## METHODS

Naturally occurring Li isotopes are 92.5%  ${}^7\text{Li}$  and 7.5%  ${}^6\text{Li}$ , while Iodine has only one natural isotope  ${}^{127}\text{I}$ . The  ${}^6\text{LiI(Eu)}$  scintillator has different concentrations of these stable isotopes with smaller amounts of Eu added as impurities. Neutrons are detected through the scintillations produced during neutron absorption by the different isotopes. In  ${}^6\text{LiI(Eu)}$  detector scintillations are mainly produced by  ${}^6\text{Li(n, } \alpha\text{)}{}^3\text{H}$  reaction due to  ${}^6\text{Li}$  cross section features and concentration.

In this work a realistic model of BSS was designed, including the  $0.4\text{ cm} \times 0.4\text{ }\varnothing\text{ cm}$   ${}^6\text{LiI}$  scintillator, without the Al layer, light pipes, detector's cask, and the polyethylene spheres. The space between the scintillator and the detector's cask was filled with air. Light pipes and cask were modeled as made of polymethyl methacrylate and aluminum respectively. Scintillator was modeled as made of  ${}^6\text{Li}$ ,  ${}^7\text{Li}$  and I; the Eu impurities were not included. The response functions were calculated for the bare detector (Ball 0) and those with the detector inserted in the spheres of 5.08 cm (Ball 2), 7.62 cm (Ball 3), 12.70 cm (Ball 5), 20.32 cm (Ball 8), 25.40cm (Ball 10), and 30.48 cm-diameter (Ball 12).

In the present calculations the scintillator cylindrical body was oriented parallel to the source-sphere axis. Each sphere-detector combination was irradiated with a neutron

beam produced by a disk-shaped neutron source. Irradiations were carried out using 23 monoenergetic neutron sources for each detector. These calculations were performed with the Monte Carlo code MCNP 4C (15) and the ENDF/B-VI cross section library (16) for 20 neutron sources whose energy was from 2.50E(-8) to 20 MeV. With MCNPX version 2.4.0 (17) and LA150 cross section library (18) the response calculations for three neutron sources, from 30 to 100 MeV neutrons, were carried. The response was defined as the number of  ${}^6\text{Li}(n, \alpha)$  reactions per incident neutron fluence based on the track length estimate of detector flux normalized to one starting particle.

In calculations reported in literature the scintillator has been modeled with different mass densities and assuming different  ${}^6\text{Li}$  enrichments, ranging from 96.1 to 100% (12, 13, 19). These assumptions result in  ${}^6\text{Li}$  atomic densities ranging from  $1.740 \times 10^{22}$  (13) to  $1.848 \times 10^{22}$  (19) atoms-cm<sup>-3</sup>. In this work the scintillator was modeled with a mass density of 3.494 g-cm<sup>-3</sup>, composed by 4.36 w/o of  ${}^6\text{Li}$ , 0.18 w/o of  ${}^7\text{Li}$  and 95.46 w/o of I, resulting in a  ${}^6\text{Li}$  atomic density of  $1.525 \times 10^{22}$  atoms-cm<sup>-3</sup>. Moderating spheres were modeled as 0.95 g-cm<sup>-3</sup> polyethylene. Atomic composition and physical data of different elements utilized to build the model were obtained from Seltzer and Berger (20). Chemical binding and crystalline effects of polyethylene during thermal neutron scattering were taken into account using the  $S(\alpha, \beta)$  treatment (15).

Spheres were modeled as a series of concentric polyethylene shells, each with a different neutron importance, increasing as the sphere center was approached. Throughout the MCNP 4C and MCNPX calculations the number of histories used for each sphere was large enough to have uncertainties less than 3%. The calculated responses were interpolated to the fifty one neutron energies of Mares and Schraube (13) and to the thirty one neutron

energies of UTA4 response matrices. The UTA4 matrix was derived from the Hertel and Davidson calculation (12). Mares and Schraube did calculate the response function for Ball 0 with the scintillator cylindrical axis perpendicular to neutron beam; this position offers a collision area of  $0.2 \times 0.4 \text{ cm}^2$ . In our case the cylindrical axis was parallel to neutron beam giving a collision area of  $\pi \times (0.2)^2 \text{ cm}^2$ , being  $0.2 \pi$  times smaller than M&S response function for Ball 0. In order to do the proper comparison our response function for Ball 0 was multiplied by  $0.2 \pi$ .

## RESULTS AND DISCUSSION

In Table I the calculated response functions are shown, the first 20 values were obtained with MCNP4C and the last three with MCNP X, each value has an uncertainty less or equal to 3%. Here, Ball 0 response function was multiplied by  $0.2 \pi$ .

The Mares and Schraube (M&S) and UTA4 response functions of Ball 0 to Ball 3 are shown in Figure 1. Here are also included the response function calculated in this work and interpolated to energy bins of M&S and UTA4. The response function for Ball 0 is strongly affected by the  ${}^6\text{Li}$  cross section shape. It can be noticed that responses are very alike; however UTA4 response function for Ball 0 has differences in the resonance region 0.1 to 1 MeV. For energies larger than 20 MeV, M&S response function has the same shape but its values are smaller than the response function obtained in this study. Also, in this energy region, UTA4 response function looks quite different, than M&S and the response function here calculated.

For Ball 2 and 3 the agreement is good and the influence of  ${}^6\text{Li}$  cross section shape is lost. The response functions of Ball 5 to 12 are shown in Figure 2 where the agreement between M&S and UTA4 response functions with the interpolated is good.

In Figure 1 and 2 can be noticed that as the sphere's diameter is increased the response functions tend to decrease for thermal and epithermal neutrons, and the response's maximum is shifted to higher energies. This is in agreement with the response matrix reported in the literature (12, 13) even regardless the type of thermal neutron detector (9, 14, 21).

For Ball 2 to Ball 12 the main differences are noticed in the low energy region and for neutrons whose energy is larger to 20 MeV, i.e. those values calculated using MCNPX. Probable explanation of this difference is attributed to the cross sections utilized by Mares and Schraube for neutrons beyond 20 MeV. They utilized the HIGH library, while in this study it was utilized those included in MCNPX. In the case of UTA4 responses calculations were carried out with DLC-41/VITAMINE-C cross-section library. However, according to Chi-square test, these differences are not significant.

## CONCLUSIONS

The fluence responses for seven Bonner spheres have been calculated for neutrons from  $2.5\text{E}(-8)$  to 100 MeV. Calculations were carried out with MCNP 4C for neutrons from  $2.50\text{E}(-8)$  to 20 MeV using the ENDF/B-VI cross-section library, while for neutrons between 30 to 100 MeV the response was obtained using the MCNPX code and the LA150

cross section library. For all the calculated cases with the spheres the  $S(\alpha, \beta)$  scattering model was utilized during the transport of low energy neutrons.

Response matrix was calculated for 23 monoenergetic neutron sources and response functions were interpolated to include the neutron energies reported in the M&S and UTA4 response matrices. Response functions are similar in shape to BSS responses regardless of thermal neutron detector except for the Ball 0 case where its response is strongly influenced by the type of thermal neutron detector.

Differences are mainly observed in the low energy region and in the case of neutrons whose energy is larger to 20 MeV; this is attributed to the different cross sections libraries utilized along the studies. The chi-square test was applied to determine if there are significant differences between the response functions here calculated and those from M&S and UTA4, from this test no significant differences were observed. However, to evaluate the effect of those differences it is necessary to use experimental data, this is an ongoing work.

## ACKNOWLEDGMENTS

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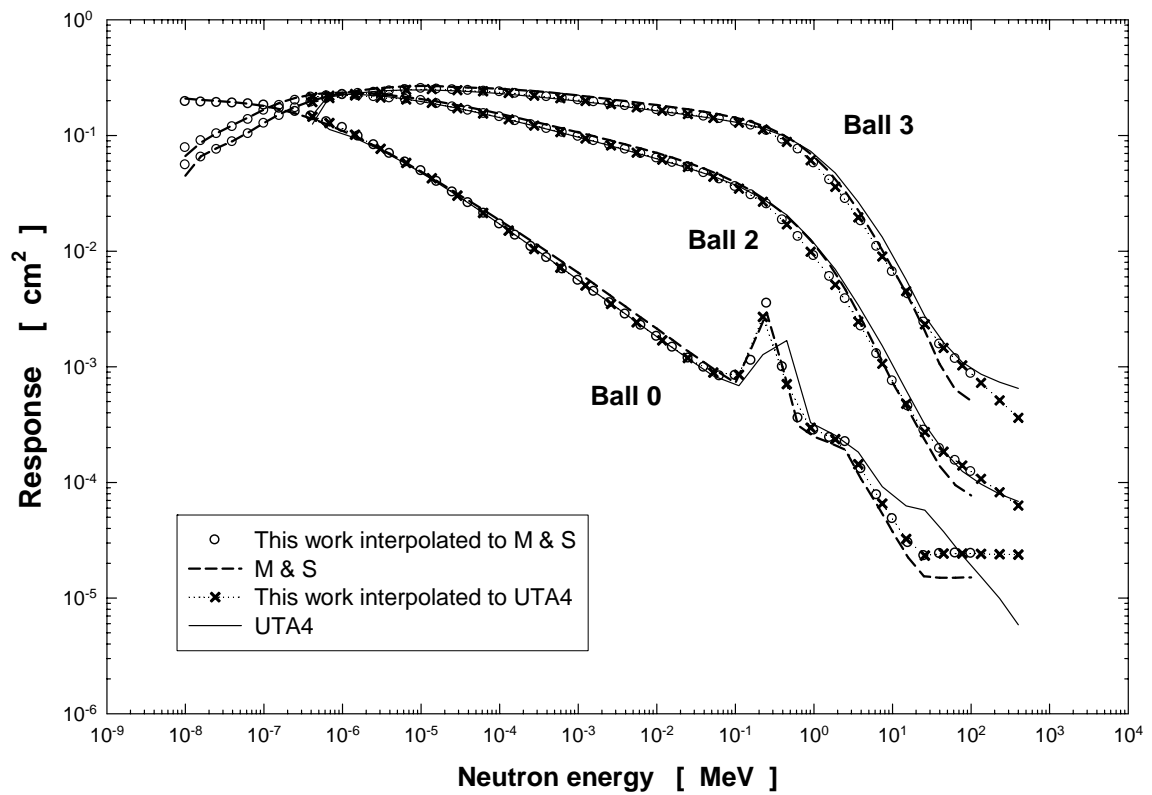


## REFERENCES

1. R.L. BRAMBLETT, R.I. EWING, T.W. BONNER, "A new type of neutron spectrometer," *Nucl. Instrum. Meth.*, **9**, 1 (1960).
2. A.V. SANNIKOV, V. MARES, H. SCHRAUBE, "High energy response functions of Bonner spectrometers," *Radiat. Prot. Dosim.*, **70**, 291 (1997).
3. V. VYLET, "Response matrix of an extended Bonner sphere system," *Nucl. Instrum. Meth. Phys. Res. A*, **476**, 26 (2002).
4. E. GALLEG0, A. LORENTE, H.R. VEGA-CARRILLO, "Characteristics of the neutron field of the facility at DIN-UPM," *Radiat. Prot. Dosim.*, **110** 73 (2004).
5. H.R. VEGA-CARRILLO, "TLDs pairs as thermal neutron detectors in neutron multisphere spectrometry," *Radiat. Measurem.*, **35**, 251 (2002).
6. J.E. SWEEZY, N.E. HERTEL, K.G. VEINOT, R.A. KARAM, "Performance of multisphere spectrometry systems," *Radiat. Prot. Dosim.*, **78**, 263 (1998).
7. R.M. HOWELL, N.E. HERTEL, Z. WANG, J.HUTCHINSON, G.D. FULLERTON, "Calculation of effective dose from measurements of secondary neutron spectra and scattered photon dose from dynamic MLC IMRT for 6 MV, 15 MV, and 18 MV beam energies," *Med. Phys.*, **33**, 360 (2006).
8. F. FERNANDEZ, T. BOUASSOULE, K. AMGAROU, C. DOMINGO, M.J. GARCIA, V. LACOSTE, V. GRESSIER, H. MULLER, "Monte Carlo calculations and validation of a gold foil-based Bonner sphere system," *Radiat. Prot. Dosim.*, **126**, 366 (2007).

9. M.P. DHAIRYAWAN, P.S. NAGARAJAN, G. VENKETARAMAN, "Further studies on the response of spherical moderated neutron detectors," *Nucl. Instrum. Meth.*, **175** 561 (1980).
10. A.V. ALEVRA, D.J. THOMAS, "Neutron spectrometry in mixed fields: Multisphere spectrometers," *Radiat. Prot. Dosim.*, **107**, 37 (2003).
11. B. WIEGEL, A.V. ALEVRA, "NEMUS-The PTB Neutron Multisphere Spectrometer: Bonner spheres and more," *Nucl. Instrum. Meth. Phys. Res. A*, **476**, 36(2002).
12. N.E. HERTEL, J.W. DAVIDSON, "The response of Bonner spheres to neutrons from thermal energies to 17.3 MeV," *Nucl. Instrum. Meth. Phys. Res. A*, **238**, 509 (1985).
13. V. MARES, H. SCHRAUBE, "Evaluation of the response matrix of a Bonner spheres spectrometer with LiI detector from thermal energy to 100 MeV," *Nucl. Instrum. Meth. Phys. Res. A*, **337**, 461 (1994).
14. H.R. VEGA-CARRILLO, B. WEHRING, K.G. VEINOT, N.E. HERTEL, "Response matrix for a multisphere spectrometer using  $^6\text{LiF}$  thermoluminescence dosimeter," *Radiat. Prot. Dosim.*, **81**, 133 (1999).
15. J.F. BRIESMEISTER (ed.) *MCNP<sup>TM</sup>: a general Monte Carlo N-particle transport code*. Los Alamos National Laboratory Report LA-13709-M. Los Alamos, NM (2000).
16. J.S. HENDRICKS, S.C. FRANKLE, J.D. COURT, *ENDF/B-VI Data for MCNP<sup>TM</sup>*, Los Alamos National Laboratory Report LA-12891. Los Alamos, NM (1994).
17. L.S. WATERS (editor), *MCNPX User's manual version 2.4.0*, Los Alamos National Laboratory Report LA-CP-02-408. Los Alamos, NM (2002).
18. M.B. CHADWICK, P.G. YOUNG, S. CHIBA, S. FRANKLE, G.M. HALE, H.G. HUGHES, A.J. KONING, R.C. LITTLE, R.E. MACFARLANE, R.E., PRAEL, L.S.

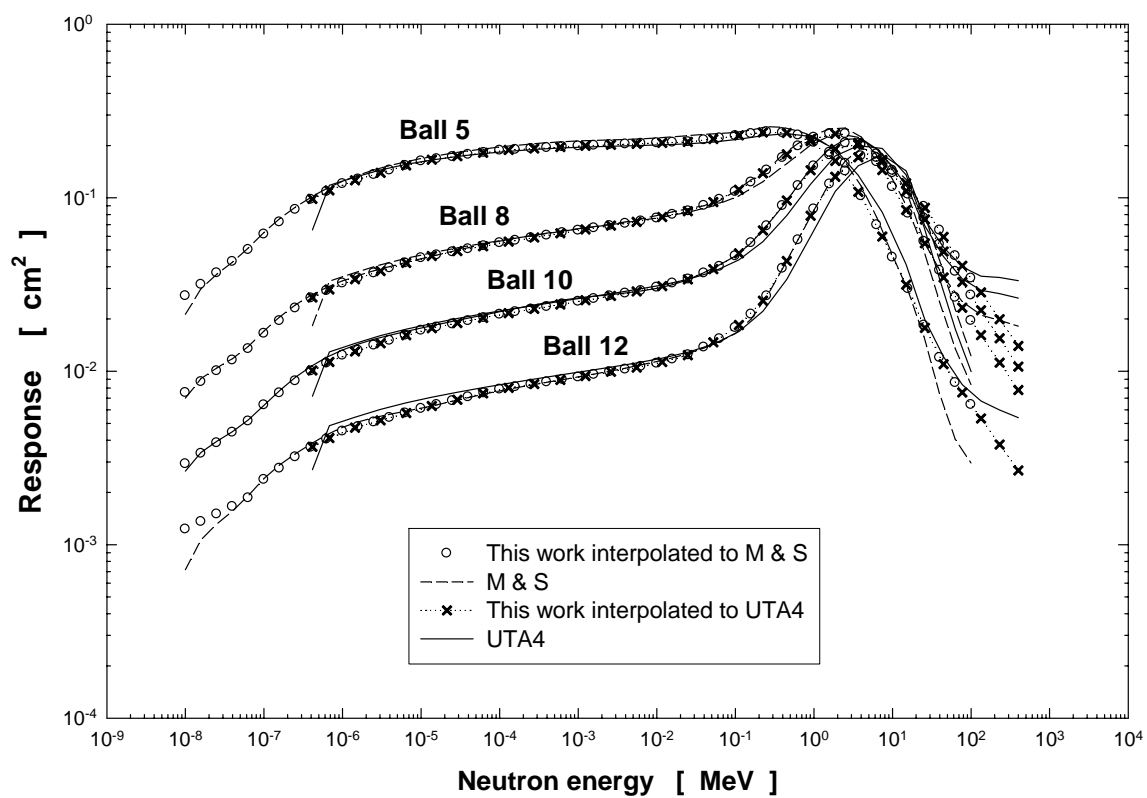
- WATERS, "Cross sections evaluations to 150 MeV for accelerator-driven systems and implementation in MCNPX, " *Nucl. Sci. Eng.*, **131**, 293 (1999).
19. E. LEMLEY, "Calculation of Bonner sphere neutron spectrometer response functions using the Monte Carlo computer code MCNP," *PhD dissertation*. University of Arkansas (1996).
20. S.M. SELTZER, M.J. BERGER, "Evaluation of the collision stopping power of elements and compounds for electrons and positrons," *Int. J. Appl. Radiat. Isot.*, **33** 1189 (1982).
21. H.R. VEGA-CARRILLO, E. MANZANARES-ACUÑA, V.M. HERNANDEZ-DAVILA, G.A. MERCADO, "Response matrix of a multisphere neutron spectrometer with an  $^3\text{He}$  proportional counter," *Rev. Mex. Fís.*, **51**, 47 (2005).



Response matrix of a BSS/<sup>6</sup>Li(Eu)

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Figure 1



Response matrix of a BSS/<sup>6</sup>Li(Eu)

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Figure 2

Neutron Energy [MeV]	Ball 0	Ball 2	Ball 3	Ball 5	Ball 8	Ball 10	Ball 12
2.500E-08	1.9149E-01	1.0291E-01	7.5136E-02	3.6748E-02	1.0007E-02	3.8539E-03	1.4974E-03
6.000E-08	1.8778E-01	1.3389E-01	1.0058E-01	4.9013E-02	1.3149E-02	5.0260E-03	1.8098E-03
1.000E-07	1.8198E-01	1.6392E-01	1.2693E-01	6.1471E-02	1.6487E-02	6.3833E-03	2.3718E-03
3.160E-07	1.5540E-01	2.1067E-01	1.8579E-01	9.2611E-02	2.5101E-02	9.4987E-03	3.4446E-03
1.000E-06	1.1658E-01	2.2572E-01	2.2392E-01	1.2022E-01	3.2155E-02	1.2329E-02	4.5055E-03
1.000E-05	4.9242E-02	1.9993E-01	2.5411E-01	1.6262E-01	4.4888E-02	1.7175E-02	6.0813E-03
1.000E-04	1.7089E-02	1.4438E-01	2.3747E-01	1.8743E-01	5.4833E-02	2.1213E-02	7.8677E-03
1.000E-03	5.5742E-03	9.7826E-02	2.0212E-01	1.9850E-01	6.4786E-02	2.5227E-02	9.2352E-03
8.150E-03	2.0054E-03	6.6165E-02	1.6932E-01	2.0611E-01	7.4559E-02	2.9709E-02	1.0816E-02
2.740E-02	1.1365E-03	5.2299E-02	1.5172E-01	2.1023E-01	8.4508E-02	3.4233E-02	1.2521E-02
7.100E-02	7.9514E-04	4.0500E-02	1.3716E-01	2.2198E-01	9.9516E-02	4.1019E-02	1.5795E-02
1.440E-01	8.8791E-04	3.1690E-02	1.2473E-01	2.3288E-01	1.1866E-01	5.2304E-02	2.0245E-02
2.500E-01	3.5693E-03	2.5564E-02	1.0980E-01	2.3958E-01	1.4377E-01	6.8504E-02	2.7006E-02
5.650E-01	3.8120E-04	1.4577E-02	8.0914E-02	2.3476E-01	1.9305E-01	1.1006E-01	5.1607E-02
1.200E+00	2.5585E-04	7.8381E-03	5.1687E-02	2.0005E-01	2.3321E-01	1.6899E-01	1.0119E-01
2.500E+00	2.2478E-04	3.8711E-03	2.8414E-02	1.4267E-01	2.3360E-01	2.0664E-01	1.5730E-01
5.000E+00	1.0023E-04	1.7104E-03	1.4526E-02	8.6909E-02	1.8739E-01	1.9962E-01	1.8290E-01
8.000E+00	6.0313E-05	9.6689E-04	8.1841E-03	5.5573E-02	1.3738E-01	1.5891E-01	1.5772E-01
1.480E+01	3.2796E-05	4.8135E-04	4.5349E-03	3.1777E-02	8.5391E-02	1.0945E-01	1.2185E-01
2.000E+01	2.2129E-05	3.7255E-04	3.3731E-03	2.4208E-02	6.8031E-02	8.9159E-02	1.0062E-01
3.000E+01	2.3996E-05	2.2632E-04	1.8670E-03	1.4818E-02	4.8035E-02	6.7671E-02	8.0683E-02
5.650E+01	2.4410E-05	1.6309E-04	1.2533E-03	9.1854E-03	2.8611E-02	4.0454E-02	4.9657E-02
1.000E+02	2.4211E-05	1.2360E-04	8.7244E-04	6.4119E-03	1.9577E-02	2.7399E-02	3.4316E-02

1.507E-05 means  $1.5097 \times 10^{-5}$

**Response matrix of a BSS/<sup>6</sup>Li(Eu)**

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**Table I**

### **Figure captions**

FIGURE 1.- Response functions for Ball0, Ball2, and Ball 3.

FIGURE 2.- Response functions for Ball 5, Ball 8, Ball 10, and Ball 12

**Table caption**

TABLE I.- Response matrix calculated with MCNP4C and MCNPX.